Modeling a Wind Turbine Synchronous Generator

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Abstract

Wind turbine power generation is rapidly becoming the preferred renewable source of electric energy. This paper presents the modelling and simulation of a wind turbine energy conversion system connected to the power grid. The wind turbine under consideration is a variable-speed variable-pitch turbine, connected to a speed-multiplying gear box to move a 3-phase wound rotor synchronous generator. The variable frequency energy produced by the generator is converted to the 60 Hz power system energy by a full power AC/DC/AC electronic converter. The control system comprises the feedback control loops for turbine, generator, rectifier and inverter. Active and reactive powers are controlled at the point of interconnection. Simulation experiments are presented for each subsystem. Results reveal the satisfactory performance of the whole wind turbine generator model.

Keywords

Wind Turbine Generator; Wind Energy Conversion System; Synchronous Generator; Electronic Converter; Control System; Modelling and simulation

Introduction

Currently, generation of electricity from wind is one of the most feasible alternatives to make use of renewable energies. Wind energy conversion systems or wind turbine generators (WTG) use a wind turbine to transform the kinetic energy of wind into mechanical energy to turn an electric generator, which transforms mechanical energy into electrical energy. Then, an electronic power converter can be used to level the electric energy to feed the power system (Prodanovic, 2003).

Most used generators in WTG include doubly-fed induction generators, direct-drive permanent-magnet synchronous generators and squirrel-cage induction generators. Even though wound-rotor synchronous generators are not so common, they are becoming a viable alternative because of grid-code requirements, such as voltage support during fault conditions; control of reactive power in a given range, limiting maximum power generation and start-up current transients (Boldea, 2006).

The control system of a WTG with wound-rotor synchronous generator includes control of nacelle orientation, wind turbine, generator excitation, power rectifier and power inverter. Development of such a control system can be carried out gradually and iteratively. At an early stage, the feasibility of the control scheme can be demonstrated in a PC-based platform using a mathematical model of the WTG. Later, the control system can be implemented and tested in the target control platform in real-time.

This paper presents the model of a wound-rotor synchronous generator WTG and a basic control scheme whose performance is evaluated through simulation experiments in a PC platform. Second section presents a summary of the wound-rotor synchronous generator WTG with full power converter connected to the power grid. Third section introduces the models of the wind turbine, synchronous generator and electronic power converter that reproduce the dynamic behaviour of a 1.5 MW WTG. Fourth section introduces a basic control scheme that regulates active and reactive powers produced by the WTG. Some typical results that show the appropriate performance of the wind turbine generator model have been available in the fifth section. The conclusion that the proposed WTG model and basic control scheme can be part of a PC-based development platform is made in the last section.

Wind Turbine Generator

As shown in Fig. 1, the WTG discussed in this paper consists of a) A wind turbine with horizontal axis 30 m three blade rotor that can produce 1.5 MW nominal power, b) A gear-box to multiply velocity from 25 rpm turbine rotor to 1800 rpm generator rotor, c) A three-phase wound-rotor synchronous generator, with self-

excited, brushless and diode rectified excitation system, d) A full power AC/DC/AC converter, with 50-70 Hz input and 60 Hz output, and e) A three-phase power transformer to connect to the power system.

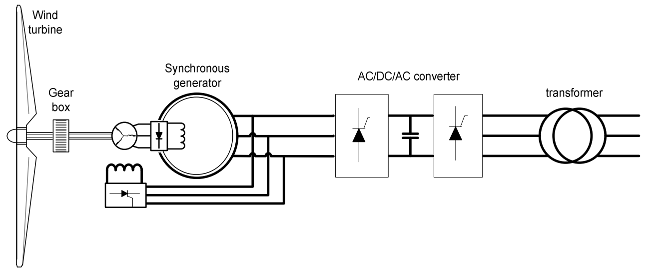

FIG. 1 WTG WITH WOUND-ROTOR SYNCHRONOUS GENERATOR AND FULL POWER CONVERTER.

The wind turbine is intended to operate at variable-speed over a wide range for the WTG to generate maximum power at low wind speeds, and to operate at constant speed and constant power at high wind speeds. Then, the conventional synchronous generator is used to produce AC electric energy of variable frequency over a wide range, and being cheaper than other generators makes them also economically viable.

The synchronous generator can be connected to a diode or controlled rectifier to produce DC electric energy and the fundamental component of the rotor current at almost unity power factor. Major drawbacks of this combination are that motor start of the WTG is not possible and the rotor current can be unstable. These can be avoided with a current-controlled rectifier (Liserre, 2003). The controlled rectifier is much more expensive. Nevertheless, it is expected that the cost can be greatly decreased in the near future, making this alternative economically viable.

The self-commutated voltage-source inverter, rated at 1.5 MW, feeds AC electric energy at 60 Hz to the power network. The inverter uses PWM (pulse width modulation) technique with a switching frequency above 3 kHz to reduce harmonics. This kind of inverter allows for reactive power flow control to connect the WTG to weak power networks. The inverter is built with IGBTs (insulated gate bipolar transistor) capable to handle 400 A at 690 V. To feed power to the network, the DC bus voltage should be constant and higher than the network peak voltage. The controlled rectifier provides the required constant voltage since the synchronous generator cannot do it at low speeds. This allows having a voltage source inverter without a step-up converter in the DC bus. The inverter may have a harmonic filter on the network side if it is necessary to comply with utility demands.

Wind Turbine Generator Model

The WTG model is intended to reproduce the dynamic behaviour of a 1.5 MW power plant. The model was programmed in Matlab/Simulink in the Windows XP operating system in a PC platform. The main components of the WTG model include the wind turbine, the synchronous generator and the AC/DC/AC power converter. Figure 2 shows the general structure of the WTG model. In what follows each one of the turbine, generator and converter blocks is explained.

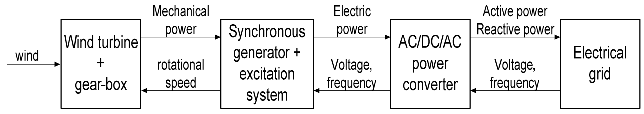

FIG. 2 GENERAL STRUCTURE OF WTG MODEL.

Wind Turbine Model

The wind turbine converts the energy of a wind flow into rotational mechanical energy. The turbine shaft drives the generator rotor through a multiplying gear box. The power P_w of a wind flow with speed v_w and density ρ across a surface with area A is given by (Bianchi, 2007):

$$P_w = \frac{1}{2}\rho A v_w^3 \tag{1}$$

The mechanical power P_m that can be obtained from the wind power depends on the turbine aerodynamic efficiency C_p:

$$P_m = P_w C_p = \frac{1}{2}\rho \pi L^2 v_w^3 C_p(\lambda, \beta) \tag{2}$$

Where the area crossed by the air is that swept by the turbine blades with radius L. The power coefficient C_p characterizes every turbine and depends on the point of operation as specified by the angular position of the turbine blades β and the turbine tip speed ratio λ that is given by:

$$\lambda = \frac{\omega_t L}{v_w} \tag{3}$$

Where ω_t is the angular speed of the turbine shaft. The power coefficient can be analytically written as:

$$\begin{gathered} C_p(\lambda, \beta) = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\right)e^{\frac{-c_5}{\lambda_i}} + c_6\lambda \\ \frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \end{gathered} \tag{4}$$

Where c_1=0.5176, c_2=116, c_3=0.4, c_4=5, c_5=21 and c_6=0.0068. Figure 3 shows C_p–λ curves for several values of β. The maximum value of C_p (C_{pmax}=0.48) is obtained for β=0 at the optimal λ (λ_{opt}=8.1).

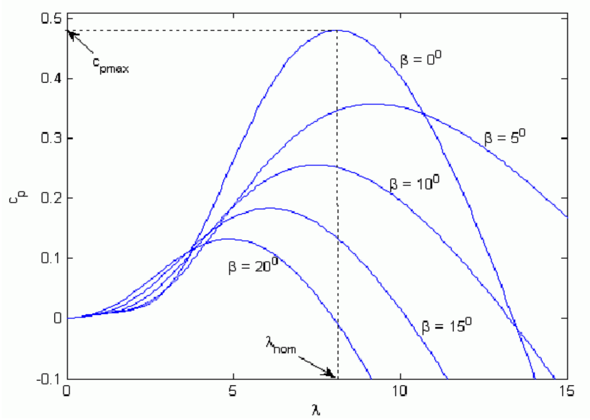

FIG. 3 C_p AND λ CURVES FOR WTG MODEL.

Assuming that the couplings among the wind turbine, gear box and electrical generator are rigid, the mechanical part of the wind turbine generator can be modelled as a single mass system with equivalent inertia constant and equivalent torque for the generator:

$$\frac{d}{dt}\omega_t = \frac{T_t - T_{ge}}{J_t + J_{ge}} = \frac{T_t - nT_g}{J_t + n^2 J_g} \tag{5}$$

Where T_t, T_g and T_{ge} are the torques and J_t, J_g and J_{ge} are the inertia constants for turbine, generator and generator equivalent, respectively. Coefficient n is the gear-box ratio $n=\omega_g/\omega_t$.

Synchronous Generator Model

The core equations of the electric generator model can be obtained from the rotor and stator circuits depicted in Figure 4. Circuits comprehend the stator winding and the rotor windings: field winding and two damping windings (k_d, k_q). Coefficients of these equations are made constant through the Park´s transformation. Then equations are normalized.

Stator equations in $dq0$ coordinates:

$$e_d = p\psi_d - \psi_q\omega_r - R_a i_d \tag{6}$$

$$e_q = p\psi_q + \psi_d\omega_r - R_a i_q \tag{7}$$

$$e_0 = p\psi_0 - R_a i_0 \tag{8}$$

$$\psi_d = -L_d i_d + L_{afd} i_{fd} + L_{akd} i_{kd} \tag{9}$$

$$\psi_q = -L_q i_q + L_{akq} i_{kq} \tag{10}$$

$$\psi_0 = -L_0 i_0 \tag{11}$$

Rotor equations in $dq0$ coordinates:

$$e_{fd} = p\psi_{fd} + R_{fd} i_{fd} \tag{12}$$

$$0 = p\psi_{kd} + R_{kd} i_{kd} \tag{13}$$

$$0 = p\psi_{kq} + R_{kq} i_{kq} \tag{14}$$

$$\psi_{fd} = L_{ffd} i_{fd} + L_{fkd} i_{kd} - \frac{3}{2} L_{afd} i_d \tag{15}$$

$$\psi_{kd} = L_{fkd} i_{fd} + L_{kkd} i_{kd} - \frac{3}{2} L_{akd} i_d \tag{16}$$

$$\psi_{kq} = L_{kkq} i_{kq} - \frac{3}{2} L_{akq} i_q \tag{17}$$

Since the connection of the synchronous generator to the AC/DC/AC power converter is balanced, the electric power output P_e can be calculated as:

$$P_e = \frac{2}{3}\left(e_d i_d + e_q i_q\right) \tag{18}$$

Finally, the excitation system is a simplified version of the IEEE AC4A exciter (IEEE 421.5, 1992) with transfer function:

$$e_{fd} = \frac{200}{0.04s + 1} V_R \tag{19}$$

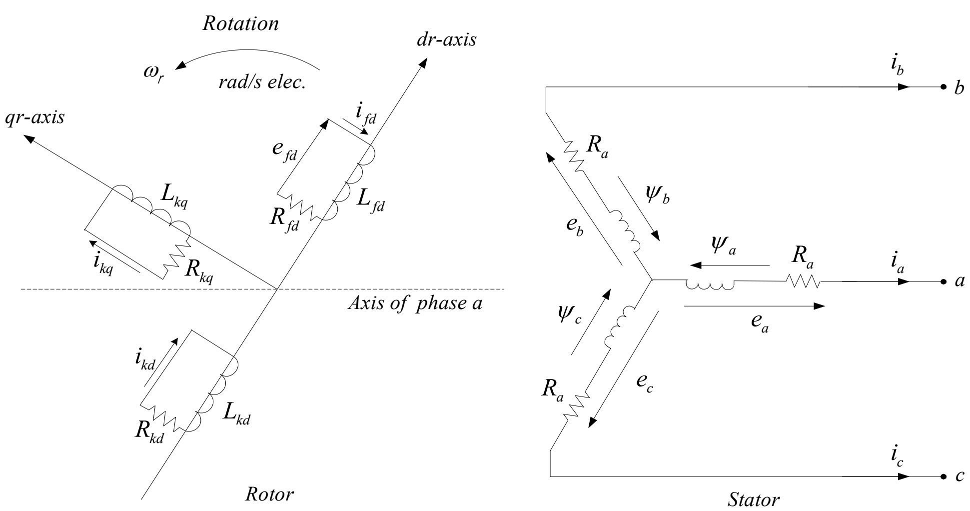

FIG. 4 ROTOR AND STATOR CIRCUITS OF A 3-PHASE SYNCHRONOUS GENERATOR.

AC/DC/AC Power Converter Model

The three-phase AC/DC/AC power converter has two components: a power converter on the generator (PCG) side and a power converter on the network (PCN) side. Both converters are built with IGBTs and use pulse width modulation (PWM). The PCN always works at the network frequency, while the PCG works at variable frequency. Both converters are voltage sources coupled back-to-back by a DC bus link, as illustrated in Figure 5.

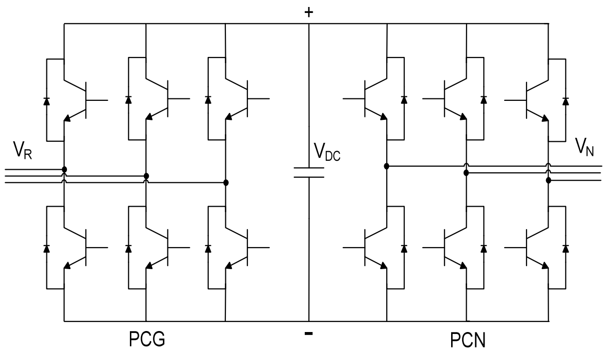

FIG. 5 AC/DC/AC CONVERTER.

The relationship between the voltage V_G at the AC terminals and the voltage V_{DC} at the DC terminals of PCG with modulation factor m_G is:

$$V_G = m_G \frac{1}{2\sqrt{2}} V_{DC} \tag{20}$$

Also, the relationship between the voltage V_N at the AC terminals and the voltage V_{DC} at the DC terminals of PCN, with modulation factor m_N, is given by:

$$V_N = m_N \frac{\sqrt{3}}{2\sqrt{2}} V_{DC} \tag{21}$$

The modulation factor is the control variable in the PWM scheme. The two previous voltage equations are only valid for 0<m<1. For larger values of m, the converters get saturated and harmonics increase at low frequencies.

Basic Control Scheme

In general, there are four control loops working simultaneously in the wind turbine generator, as shown in Figure 6. The wind turbine uses a parallel-cascaded control scheme to regulate the shaft speed in accordance to the incoming wind flow speed by adjusting the angular position of the rotor blades. The main loop provides a control signal from a P controller that compares the turbine shaft speed ω_t to the shaft speed reference ω^*_t. Additionally, the power control loop provides a control signal to compensate the main loop. This control signal is provided by a PI controller that compares the active power produced by the wind turbine generator P with the power reference P^*.

The synchronous generator has an AVR (Automatic Voltage Regulator) system that implements a control loop to regulate the generator terminal voltage V_g to the voltage reference V^*_g, usually set by the operator (Fig. 6). The terminal voltage is compared to the voltage reference by the AVR that evaluates a PI control algorithm and feeds control voltages to a PWM module. This module generates the modulation factor m_{AVR} for the IGBT-based rectifier, which provides the required field voltage V_{fd} and current I_{fd} for the auxiliary generator. The auxiliary generator provides power to the field of main generator through a full-wave diode rectifier.

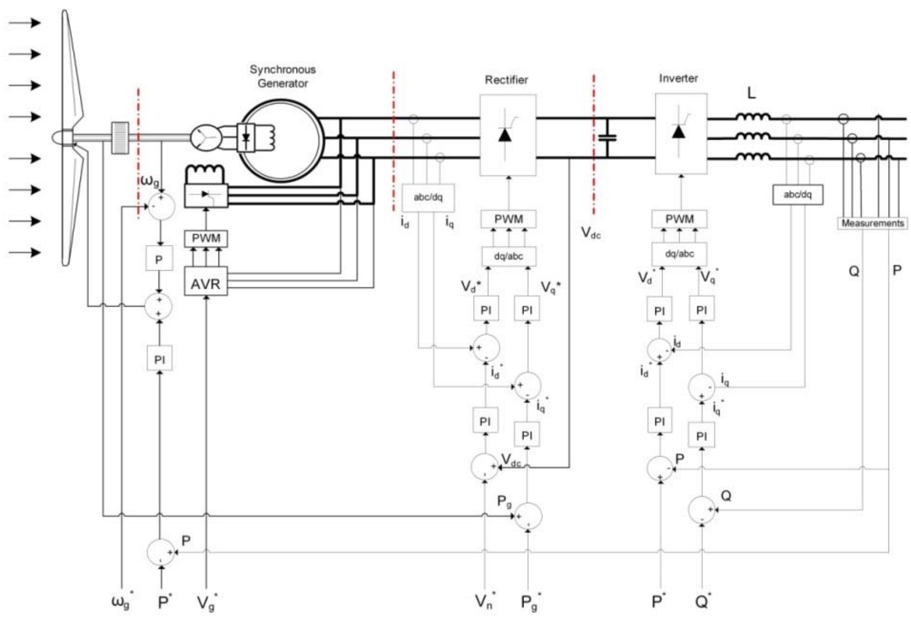

FIG. 6 CONTROL SYSTEM BLOCK DIAGRAM OF WIND TURBINE GENERATOR WITH SYNCHRONOUS GENERATOR AND FULL POWER CONVERTER.

The basic voltage control scheme can be readily enhanced in two ways. First, it can control the DC bus current and prevent it from raising uncontrollably. With this purpose, the generator terminal voltage must be limited to be below 90% of the PCN AC voltage. Second, the generator voltage control can be utilized to optimize the generator-converter efficiency. To achieve this, the voltage reference should be generated in terms of the DC current entering the PCN.

The control scheme of the PCG includes two series-cascaded control loops aimed to regulate the DC bus voltage V_{DC} and the active power produced by the generator P_g or the generator counteracting electric torque T_e. In the voltage control loop, the outer control loop compares the measured DC bus voltage V_{DC} with the reference V^*_{DC}, evaluates a PI control algorithm and provides a control signal that works as the *d*-axis current reference I^*_d for the inner control loop. The *d*-axis current I_d is obtained by applying Park´s transformation to the measurements of generator phase currents. The inner current loop evaluates a PI control algorithm and generates the *d* component of the control voltage V_d.

On the other hand, the power control loop implements an outer loop to control power produced by the synchronous generator P_g using a PI controller, which generates the q-axis current reference I^*_q for the inner control loop. The q-axis current I_q is obtained from the measurements of generator phase currents. The inner loop evaluates a PI control algorithm and generates the q component of the control voltage V_q. Then, both control voltages V_d and V_q are composed to obtain the three phase control voltages that feed the PWM module, which generates the modulation factor m_G for the PCG.

Similarly, the PCN control scheme also includes two series-cascaded control loops. In this case, it is aimed to regulate the active power *P* and reactive power *Q* produced by the wind turbine generator. In the active power control loop, the outer control loop is compared with *P*, calculated from phase voltages and currents measured after the output inductances, with the reference active power reference *P**. Then a PI controller provides a control signal that works as the PCN d-axis current reference I^*_d for the inner control loop. The d-axis current Id is obtained by Park´s transformation of the measurements of PCN three-phase AC currents. The inner loop also has a PI controller that generates the d component of the control voltage V_d. On the other hand, the reactive power control loop implements an outer loop to control the reactive power *Q* produced by PCN using a PI controller, which generates the PCN q-axis current reference I^*_q for the inner control loop. The PCN q-axis current I_q comes from measurements of PCN three-phase AC currents. The inner current loop provides the q component of the control voltage V_q using a PI controller. Then, both control voltages V_d and V_q are composed to obtain the three-phase control voltages to feed the PWM module to generate the modulation factor m_N for the PCN.

It is important to keep in mind that the purpose of proposed control scheme is to demonstrate the feasibility of the WTG model and to be a reference control scheme for further enhancement.

Simulation Experiments

This section presents the results of some simulation experiments. Experiments include simulations of WTG subsystems and the whole WTG as well, such as: a) Response of wind turbine blade pitch angle, b) Response of PCN current regulator, c) Response of active and reactive powers with separate PCN, and d) Behaviour of voltages, current and active and reactive powers at the PCN with the complete WTG model simulation.

Figure 7 shows the response of pitch angle around 0 degrees for 12 m/s wind speed during 3 seconds steady-state simulation experiment. It is known that the pitch angle should be commanded at 0 degrees, or at slightly negative values, for wind speeds between the cut-in speed (4 m/s aprox) and 12 to 14 m/s, to capture the most energy from the wind.

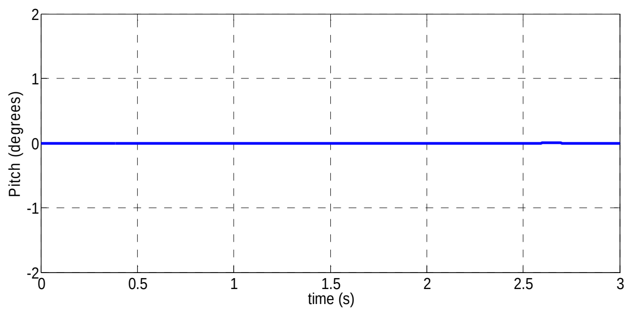

FIG. 7 STEADY-STATE RESPONSE OF PITCH ANGLE AT 12 M/S WIND SPEED.

Above the range of 12 or 14 m/s, the pitch angle should be commanded from 0 degrees up to around 20 to 24 degrees. The objective in this range is to degrade the wind turbine performance to keep constant the power or torque generated by the turbine. At wind speeds

above 25 m/s, the pitch angle should be fully opened (90°) to protect the WTG mechanical structure.

Figure 8 shows the response of PCN when controlled solely by the inner current control loops. In this case, the d-axis component of PCN phase currents is commanded to stay constant at 1 p.u. In the meantime, the q-axis component is commanded large step changes, from 0 p.u. to +0.5 p.u. to -1.0 p.u. and back to 0.0 p.u.

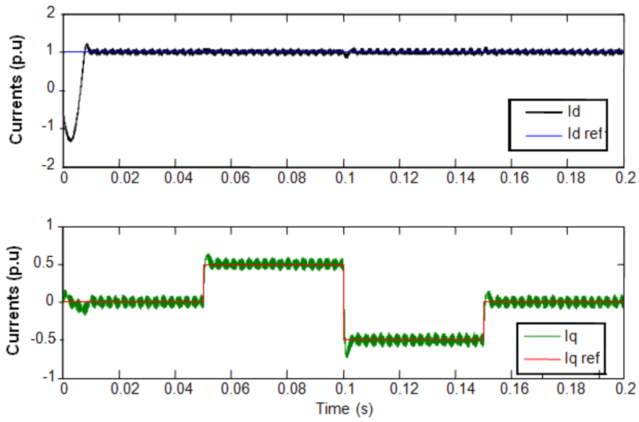

FIG. 8 RESPONSE OF I_d AND I_q CURRENTS OF PCN TO WIDE STEP CHANGES IN CURRENT REFERENCE I^*_q.

It can be seen that I_d reaches I^*_d=1 p.u. very rapidly and is kept all the time, with unnoticeable influence of the changes in I_q. On the other hand, current I_q follows all changes in I^*_q very nicely throughout the range of operation. This result is very important since it shows that active power can be commanded to remain constant and reactive power may vary through the whole range of operation.

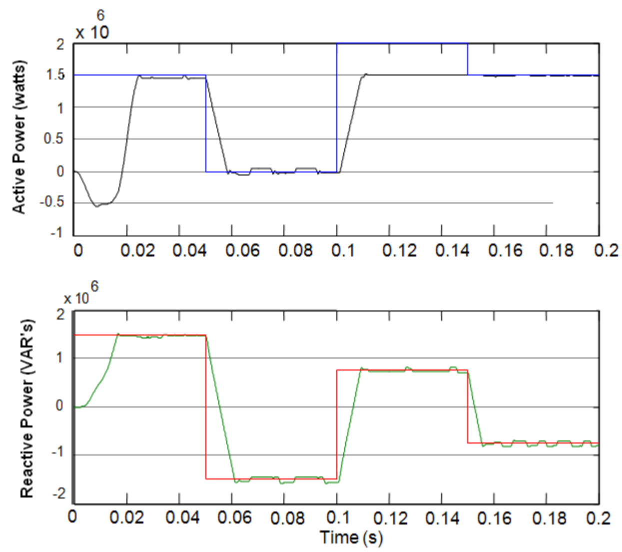

FIG. 9 WIDE RANGE RESPONSE OF ACTIVE AND REACTIVE POWERS AT PCN.

Additionally, Figure 9 depicts the response of PCN when controlled with the active power, P, and the reactive power, Q, outer control loops and the inner current I_d and I_q control loops. In this simulation experiment, both the active and reactive powers are simultaneously commanded large step changes. The active power is commanded to go from 1.5 MW (full load) all the way to 0 MW, then to go up to 2.0 MW (out of range) and finally go back to 1.5 MW. At the same time, the reactive power is commanded to go from 1.5 MVAR (full generation) down to -1.5 MVAR (full consumption), then go up to 0.8 MVAR and back to -0.8 MVAR.

In this simulation experiment, it can be seen that the response of active power is quite good and fast, with a settling time of 0.01 s. As well, although a commanded value out of range, it will not go beyond the established capacity, thus limiting short circuit currents. Active power is always commanded positive values to work as a generator. On the other hand, response of reactive power is also good and fast (settling time about 0.01 s). Reactive power Q follows all changes throughout the range of operation, including positive and negative values, meaning that can provide or consume reactive power at the point of connection to the power system. Therefore, the WTG can be used to support voltage and contribute to power system stability.

Figure 10 shows the behaviour of the whole WTG model including wind turbine, synchronous generator with excitation system and both power converters. In this simulation, the WTG is commanded to undertake a large change in the reactive power Q generated when the WTG operates in steady state.

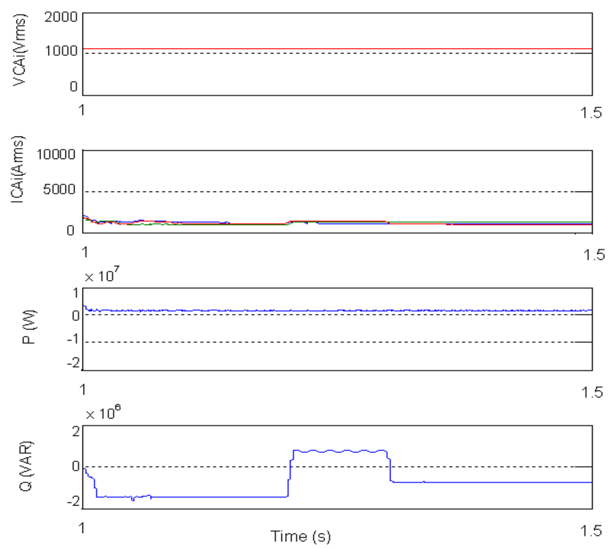

FIG. 10 RMS VOLTAGES AND CURRENTS ACTIVE AND REACTIVE POWER AFTER INVERTER.

Reactive power control is a major requirement for the WTG to cope with voltage dips in the electric network during fault conditions. Results mainly show that the proposed WTG model and control scheme respond adequately to mitigate the effect of the voltage transient and collaborate to system voltage stability. Reasonable values for major variables, such as inverter terminal voltage V_{CAi}, inverter line current I_{CAi}, active power output P and reactive power output Q are obtained. This means the WTG will be able to satisfy grid-code requirements, such as voltage support during fault conditions; and control of reactive power in a given range, limiting the maximum amount of power generation.

Conclusions

This paper presented the model of a wind turbine, with synchronous generator and full power converter, and its complete control system. Results of simulation experiments for each subsystem of the wind turbine demonstrate satisfactory performance, with reasonable steady-state values and transient responses. The model is embedded in a user-friendly environment, which provides easy access to the variables and parameters of the model and the control system. Therefore, the proposed model and its basic control scheme can be used as a starting points or reference designs for further development of WTG models and control systems.

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